AN OBSERVATIONAL STUDY OF THE UPPER WIND CIRCULATION AROUND TROPICAL STORMS

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ABSTRACT

All available rawin reports taken within the circulation of tropical storms are combined to obtain a generalized pattern of the upper wind circulation. The cyclonic circulation decreases rapidly with height and by 45,000 ft the circulation is anticyclonic beyond 3° latitude from the center. The relative vorticity in the upper troposphere was found to be negative and great enough in magnitude so that zero absolute vorticity is approached.

Introduction

The tropical cyclone has long been recognized as a warm core low (cf. Shaw, 1922) in which, from hydrostatic considerations, the pressure difference between the storm center and the environment, and consequently the cyclonic circulation, must decrease with elevation. Many of the early investigators insisted that the tropical cyclone was a shallow system that completely disappeared below 3 km. Haurwitz (1935) showed convincingly that a tropical cyclone with a central pressure much below 1000 mb must necessarily extend through a large portion of the troposphere. This was done by computing, from a form of the hypsometric equation, the mean temperature in the storm center which would be required in order to nullify the pressure gradient at various levels. Only when the upper extent of the storm was assumed to be at least 10 km did the mean temperature appear reasonable. Haurwitz pointed out that the storm circulation did not necessarily end at the height of zero pressure gradient but that perhaps above this level the pressure field was oppositely directed, thus providing an outflow mechanism for the air which had flowed into the storm at lower levels and ascended near the center.

Pilot balloon observations which had been taken in the tropical cyclone circulation were generally in agreement with this scheme. However, the heavy cloud systems about the storm usually prevented the collection of data very near the center. Only after the introduction of radar and RDF winds in the 1940's was it possible to obtain winds extending to great heights near the storm center. These reports showed clearly the extension of the cyclonic circulation through great depths, often to 40,000 ft and higher, and showed some evidence of an upper outflow pattern. The number of wind reports available at any given time or for any one storm has been so meager that it has been impossible to attempt any detailed synoptic study of the upper circulation pattern of the tropical storm.

For this study, wind data were collected to determine the mean upper circulation pattern of the tropical cyclone. The data used were taken during the years 1945 through 1951 at island and coastal stations within the extent of the surface circulation of tropical cyclones. In the beginning the storms were divided into large and small Pacific storms and Atlantic storms. However, it was necessary to discard this classification and combine all the data since the number of reports turned out to be rather small for each of the classifications. Some of the difficulties of combining data from storms of different size, intensity, and stages of development were anticipated and certain precautions, discussed below, were taken.

Type and Amount of Data

The Pacific storm tracks were obtained from Navy and Air Weather Service reports and also from publications of the Royal Observatory, Hong Kong. In the Atlantic the tracks were taken from the Monthly Weather Review. Many of the data were from the Northern Hemisphere Historical Maps and from these only one report per day was available. Data taken from the Daily Upper Air Summaries and teletype reports provided 2-4 observations per day. For the years 1948 and 1950 there were no Pacific data available.

The reports used in this study were located from 2°-6° latitude from the storm center. The number of rawin reports available within 2° latitude of the center was so small that they were not included. Most of the Pacific storm tracks used were between 10°N and 30°N latitude, while most all of the Atlantic storms fell between 20°N and 30°N. An attempt has been made to use only reports taken in the mature storms. No winds have been used from the circulation of developing storms, dissipating storms, or from storms which had recurved into middle latitudes. Further, to make the data as homogeneous as possible only those wind reports which extended to at least 30,000 ft have been used.

The lowest level taken was 4000 ft since data for the 700-1000 ft level had already been collected in a previous study by Hughes (1952). The levels used here were 4000 ft, 7000 ft, 10,000 ft, 18,000 ft, 30,000 ft, 40,000 ft and 45,000 ft. The number of winds at each level from 4000 ft to 30,000 ft was approximately 130, tapering off to 88 reports at 45,000 ft. More than half of the reports were from Atlantic stations.

Processing of the Wind Observations

The first step in the processing of the data was to break down each wind report into its instantaneous tangential and radial components about the storm center. This was done by plotting each report on a polar diagram (Fig. 1) with the direction of motion of the storm taken along the 0° axis. The distance along the radius vector from the storm center to the reporting station and the angle between this radius vector and the velocity vector of the storm motion were determined from the storm tracks. Then using these values as coordinates, the wind vector was plotted on the polar diagram. The angle between the radius vector and the wind vector was measured, and by multiplying the wind speed by the sine and cosine of this angle, the tangential and radial components were obtained. Cyclonic circulation and inflow have been taken as positive.

Sources of Error

The accuracy of the tangential and radial components obtained in the manner described above is affected by (a) inaccuracies in the reported position of the storm center, (b) the storm movement during the 30-60 minutes taken for the balloon ascent and (c) the fact that the balloon does not ascend vertically above the station. This is independent of errors in the wind observation itself.

Errors in the reported position of the storm undoubtedly introduce significant errors in the computed wind components in individual cases. However, since these errors tend to be random, they should have no significant effect on composite features.

The effect of the storm movement during the pibal or rawin run has been considered small in comparison with the other sources of error. This effect could not be taken into account since the instantaneous storm position and movement are never known with sufficient accuracy.

The drift of the balloon away from the reporting station during its ascent, if not corrected for, introduces errors in the computed wind components. Further, these errors are systematic in the sense that computed radial velocities are always too large, i.e., excessive inflow or deficient outflow, and the tangential velocities are too small in areas of inflow and too large in areas of outflow. This effect is of most importance where the balloon drift and the turning of the wind along a trajectory are the greatest. Therefore, all reports within 4° latitude of the storm center have been corrected by plotting the balloon trajectory and determining for each level the correct position of the wind observation with respect to the storm center. At the 45,000 ft level in some cases the drift was in excess of 30 km and the correction as large as 5 knots. The correction is most important for the smaller of the two wind components. Therefore, it is usually more important for the radial component in the low levels and becomes more important for the tangential component at higher levels.

It was assumed that the storm center is vertical throughout the troposphere. This assumption appears to be quite valid, as the slope is usually too small to be detected and no consistent direction of slope has been observed.

Method of Combining Data

The reported winds at all levels in the storm circulation were processed in the manner described above. The wind components -- total, radial and tangential -- and the distance from the storm center were tabulated for individual reports for each level and octant. At a given distance from the center, for example 2°-3° latitude, the individual values of the components were found to vary over a large range. This wide variation was not completely unexpected since all sizes of storms had been used. However, the combination of these data to give a composite picture of the circulation presented a difficult problem. The number of values in any one degree latitude strip in a given octant was not large enough so that an average would have had much significance. Often there were less than five reports and mean deviations were as large as 10 knots.

Because of the difficulty of obtaining significant mean values, a somewhat more qualitative technique has been used in combining the data. Scatter diagrams of the wind velocity versus the distance from the storm center were prepared for the total, tangential, and radial components for each octant at each level. First, curves were drawn to best fit the data; then, the curves were adjusted to make them as internally consistent as possible without violating the data. The following considerations have been used in making these curves consistent: (a) the tangential and radial velocity fields when added vectorially should give the total velocity field, (b) the field distribution of the components should show some degree of regularity about the storm and in the vertical, for example, the location of the octant of maximum winds would not be expected to vary wildly about the storm from level to level, and (c) the vertical shear should be negative and not exceed certain limits imposed by the rather flat temperature field known to exist about the tropical storm. After the curves were adjusted the wind components were tabulated at 1° latitude intervals for each octant at each level. For want of a better term, the values read from the adjusted curves have been referred to as means.

This smoothing of the data necessarily resulted in a much simplified picture of the storm circulation. However, in view of the differences between individual storms, the non-steady conditions usually present within a storm, and the micro-structure of the storm circulation, a mean circulation should be expected to show only the large scale features which are generally found in the tropical storm.

The Tangential Component

A field distribution of the tangential velocity was drawn at each level using the mean values obtained from the scatter diagrams. These charts are shown in figures 2a-e. Since the patterns were similar at 4000 ft, 7000 ft, and 10,000 ft, only the 7000 ft chart has been reproduced.

These charts show that for any level at a given radius the tangential component varies over a considerable range. For example, at the 7000 ft level (Fig. 2a) the tangential component at 5° latitude from the center is 30 knots in octant III (cf. Fig. 1) while it is only 8 knots at the same distance out in octant VII. At all levels the greatest positive tangential components (cyclonic) are found in octant III. The smallest tangential components are in octant VII.

Negative tangential components (anticyclonic flow about the storm center) first appear at 30,000 ft in the outer portion of the circulation. At 40,000 ft and 45,000 ft a small core of cyclonic circulation is completely encircled by the anti-cyclonic circulation. The decrease with height in the extent of the cyclonic circulation of the storm is shown quite clearly by these charts.

The appearance of the greatest cyclonic tangential components in octant III and the lowest in octant VII are a reflection of the superimposed rotation and translation of the storm. In octants II and III a large component of the storm motion is additive to the rotation, while in octants VI and VII a large component is opposed to the rotation.

The magnitude of the mean tangential components near the storm center shown by figure 2a-e, as well as the magnitude of the radial components, are probably somewhat less than those found in a "typical" cyclone. This bias toward weaker winds results from the fact that the probability of obtaining a wind report within 4° latitude of the storm center is much less when the surface wind is strong than when it is relatively weak.

Average values of the tangential component around the storm were obtained and the vertical shear was computed from them (Fig. 3). This shear is a maximum at the highest levels and closest to the storm center.

Computation of Steering Current

If the observed storm circulation is a combination of a field of rotation and a field of translation, then we can obtain the field of translation by taking half the difference between the tangential components along the axis normal to the direction of motion on both sides of the storm center. For instance, say that the tangential component is east, 50 knots, at a point 3° to the north of a westward moving storm and west, 30 knots, at a point 3° to the south. Then the steering current is east, 10 knots.

This computation was carried out in the band from 2° to 4° latitude from the center at all levels between 4000 and 30,000 ft. The steering current so obtained therefore represents the mean flow of the troposphere from the vicinity of the surface to 300 mb over a band 8° latitude wide. Its speed, taken as the pressure weighted mean of the computations at all available levels, was 9.7 knots. The average speed of movement of the storms included in this study was 11 knots. Evidently, the small difference is fully within the limitations of the data.

If we are to be certain that the storms move with the steering current in which they are embedded, we must repeat the above calculation along the axis parallel to the direction of motion. This computation will tell us whether the steering current is entirely in the direction of motion or whether it has a component normal to it. It is the result of the computation that the normal component of the steering current is less than one knot, and therefore should be considered as zero within the limits of accuracy of the data.

It follows that in the mean, tropical storms move in the direction and with the speed of the steering current, if the latter is defined as the pressure weighted mean flow from the surface to 300 mb and extending over a band 8° latitude in width centered on the storm. Herewith, the validity of the old concept of steering has been affirmed. We must presume that marked departures of storm paths from steering, as sometimes reported in the literature, are due mainly to inadequate knowledge of the horizontal and vertical wind structure in individual cases, and also to attempts to oversimplify the problem by trying to find a "steering level." Riehl and Burgner (1950) suggested that the concept of a steering layer must replace that of steering level, and Yeh (1950) found that in his model the storms move on the average with the mean speed of the steering current. The present computations provide observational verification for both of these statements.

Mean Vorticity

The mean relative vorticity of annular rings can be computed from the tangential component alone, by obtaining the circulation around these rings and dividing by the area, $\zeta_r = 2\frac{r_0 v_0 - r v}{r_0^2 - r^2}$, where r_0, r are the radius and v_0, v are the tangential velocity of the outer and inner portion of the rings, respectively. The mean vorticity was computed for rings of 1° latitude width from 2° to

6° from the storm center. The computed values are shown in a mean vertical cross-section (Fig. 4).

The mean relative vorticity at 900 mb has a maximum in the 2°-3° latitude ring and decreases to zero in the 5°-6° ring. The area of positive vorticity decreases rapidly with height and at 500 mb only the 2°-3° ring has a positive value. Above 500 mb the negative relative vorticity is found everywhere in this 2°-6° region. The horizontal shear is everywhere anticyclonic (Fig. 2a-e). At low levels the curvature is cyclonic and this term is greater in magnitude than the shear, resulting in regions of positive vorticity. The magnitude of the anticyclonic shear increases with height up to 200 mb, especially near the storm center. The curvature term decreases with height and also radially from the center, the most rapid decrease in both directions occurs nearest to the storm center. These terms combine to give negative relative vorticity which reaches a maximum about 3°-4° latitude from the center and at 200 mb.

The fact that storms of different size and intensity were combined necessarily contributes to mean shears somewhat smaller than would be observed in individual cases. Even so the relative vorticity at 200 mb reached a negative value of 4.9×10^{-5} sec^{-1} for the 3°-4° ring. As the Coriolis parameter, within the latitude range of the majority of the storms, is between 5.0 and 6.1×10^{-5} sec^{-1}, the magnitude of the mean absolute vorticity is somewhere in the range of 0 to 10^{-5} sec^{-1}. It would thus appear that in individual cases, limited areas with negative absolute vorticity are likely to exist.

Radial Component

The accuracy of the radial component taken from the adjusted curves of the scatter diagrams is open to considerable doubt. This is because, throughout a deep layer roughly from 10,000 ft to 30,000 ft, the radial component of the individual wind reports vacillated between inflow and outflow. Since the inflow and outflow angles were in general quite small in this layer, the computed radial components are very sensitive to errors in the storm position and movement. Only at the 40,000 ft and 45,000 ft levels where the radial component is of the same order of magnitude as the tangential could much confidence be placed in the radial value. However, sufficient consistency was shown between the 4000 ft, 7000 ft, and 10,000 ft mean radial distributions so that the low level radial pattern appears to be of significance. The 7000 ft level has been reproduced although the exact values may be somewhat in error.

The mean inflow at the 7000 ft level is about 30 per cent of that shown for the 1000 ft level by Hughes (1952). Thus the strong inflow is limited to a relatively shallow layer near the surface. The low level distribution of the radial velocity (Fig. 5a) shows a large area of inflow in octants III - VII and a smaller area of outflow in octants VIII, I and II. The same pattern, indicating a movement of the storm with the basic current was shown at all levels. The larger area of inflow, resulting in net inflow near the surface, became smaller with height. The areas of inflow and outflow were nearly balanced in the 10,000 ft to 30,000 ft region and at the upper levels the areas of outflow became much more widespread (Fig. 5b). At these upper levels outflow of the order of 30 knots was found on the forward side of the storm, octants I and VIII, while weak inflow is still present in octants III and IV.

Resultant Winds

The radial and tangential components have been combined to obtain the field distribution of the resultant winds. Streamlines have been drawn for 7000 ft and for 45,000 ft (Fig. 6a,b). The streamline pattern for the 7000 ft level is considered essentially correct, even though the radial component is somewhat in doubt. At this level the radial in general is much smaller than the tangential and has little effect on the resultant.

The streamline pattern and the velocity distribution for the 7000 ft level are somewhat similar to those observed synoptically. For example, the area of streamline convergence and strongest velocities on the rear side of the storm are often shown by aircraft reconnaissance data (cf. Thompson, 1951).

The streamline pattern at 45,000 ft shows a pattern very different from that of the low levels. Cyclonic circulation is observed near the storm center, becoming anticyclonic at 3°-4° latitude from the storm center. The extent of the influence of the tropical cyclone appears to be greater to the right of the storm than to the left. The fairly straight flow at 5°-6° latitude from the center in octants VI and VII appears to be outside the circulation of the tropical storm.

The closed anticyclonic cell indicated by the streamlines at the upper levels does not appear to be a fictitious feature introduced by the averaging, since in particular storms individual stations in octants II and III show a rapid clockwise turning of the wind with time (cf. La Seur and Jordan, 1952). Also, individual station reports verify the inner core of cyclonic circulation shown at the 45,000 ft level.[1]

A different pattern is shown by subtracting the average storm movement, 11 knots, from the streamline pattern at 45,000 ft (Fig. 7) to obtain the motion of air particles relative to the storm center. The resulting pattern shows outflow in all the octants. This large outflow at the higher levels agrees with the pattern discussed by Riehl (1948).

It is the principal result of figures 6b and 7 that in the high troposphere a ring of clockwise circulating air surrounds an inner core where the circulation is still cyclonic. In the shear zone between these two rings we observe smaller clockwise rotating eddies. Whether or not the particular location of these eddies as given in figures 6B-7 holds in all individual cases is open to question. But it is reasonable to suggest that the basic flow properties suggested by these figures will be observed in most storms. These properties are sketched again in model form in figure 8. This model tries to represent mainly the tangential flow component. We can obtain streamlines corresponding to figures 6b-7 by adding appropriate outflow components. The choice of the number of clockwise subeddies in figure 8 is, of course, arbitrary. But it may be suggested that this number is related to the number of "radar bands" (Wexler, 1946-1947) found spiralling toward the center in the low levels.

[1]For example Miami, Fla., Aug. 27-28, 1949; Guam, M. I.; Sept. 12, Oct.1, Oct. 4-5, 1945; Okinawa, R. I., July 19-20, 1945.

Summary

The pattern of the wind circulation about the tropical cyclone indicated by this study is in general agreement with the model of Riehl (1951). The major region of inflow is confined to the lowest 10,000 ft and the outflow occurs principally above 30,000 ft. In the region 10,000 ft- 30,000 ft the mean radial flow may be directed outward or inward depending upon such factors as the size and intensity of the storm and its stage of development.

The mean tangential component decreases with elevation much more rapidly in the outer portion of the storm than near the center. Thus the cyclonic circulation of the storm covers much less area at the 40,000 ft level than it does at the 10,000 ft level. Associated with the more rapid decrease of the tangential component in the outer portions, the horizontal shear becomes much stronger at the upper levels. The anticyclonic shear is sufficiently strong so that even in this mean picture the absolute vorticity approaches zero. The outflow occurs just at those levels where the absolute vorticity is the smallest.

Acknowledgment

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REFERENCES

1. Shaw, N. 1922: The birth and death of cyclones. London, Geophysical Memoirs, vol. 2, no. 19, pp 213-227.

2. Haurwitz, B., 1935: The height of tropical cyclones and of the "eye" of the storm. Mo. Wea. Rev., vol. 63, pp 45-49.

3. Hughes, L. A., 1952: On the low-level wind structure of tropical storms. (To be published)

4. Riehl, H. and N. M. Burgner, 1950: Further studies of the movement and formation of hurricanes and their forcasting. Bull. Amer. Met. Soc., vol. 31, pp 244-253.

5. Yeh, T. C., 1950: The motion of tropical storms under the influence of a superimposed southerly current. J. Meteor., vol. 7, pp 108-113.

6. Thompson, B. W., 1951: The upper-level flow-structure near typhoons. Quart. J. Roy. Met. Soc., vol. 77, pp 272-282.

7. La Seur, N. E. and C. L. Jordan, 1952: A Typical weather situation of the typhoon season. Dept. of Meteor., Univ. of Chicago.

8. Riehl, H., 1948: On the formation of typhoons. J. Meteor., vol. 5, pp 247-264.

9. Wexler, H., 1946-1947: Structure of hurricanes as determined by radar, Ann. N. Y. Acad. Sci., vol. 48, pp 821-844.

10. Riehl, H., 1951: Aerology of tropical storms. Compendium of Meteorology, pp. 902-913.

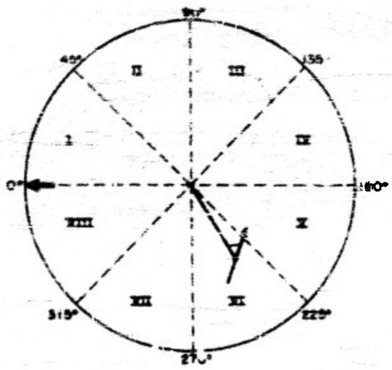
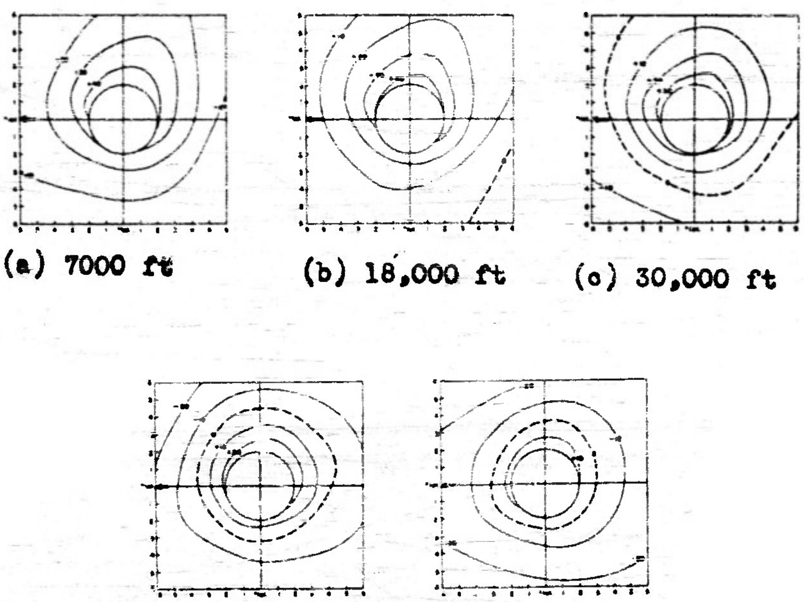


Fig. 1. Reference diagram for obtaining the wind components. Each storm was divided into octants which were numbered clockwise from the direction of motion.



(a) 7000 ft (b) 18,000 ft (c) 30,000 ft

(d) 40,000 ft (e) 45,000 ft

Fig. 2. Tangential velocity (knots). Positive values cyclonic, negative values anticyclonic. Inner circle marks boundary of data.

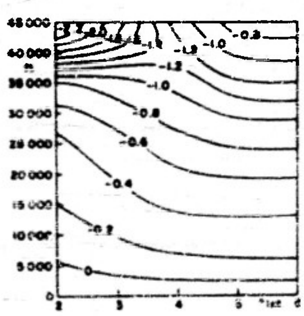


Fig. 3. Cross-section of the vertical shear of the tangential velocity (knots per 1000 ft).

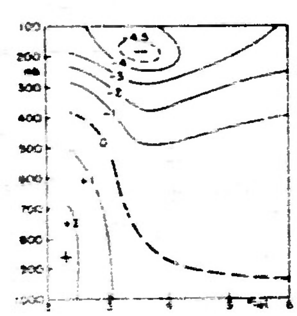
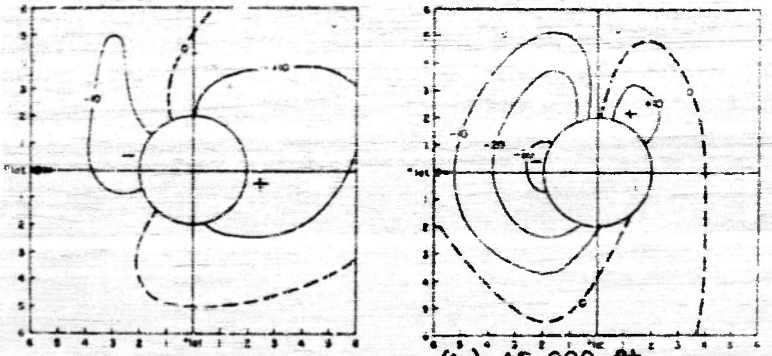
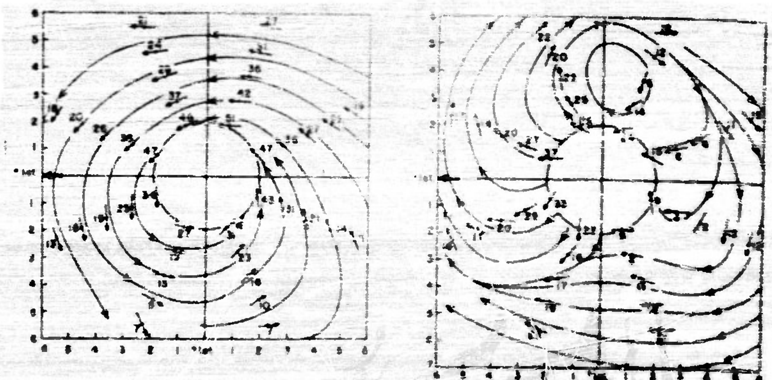


Fig. 4. Vertical cross-section of the relative vorticity (10^{-5} sec^{-1}).



(a) 7000 ft (b) 45,000 ft

Fig. 5. Radial velocity (knots). Positive values directed toward the center, negative values directed away from the center. Inner circle marks boundary of data.



(a) 7000 ft (b) 45,000 ft

Fig. 6. Streamlines drawn from resultant winds. Total wind speed (knots).

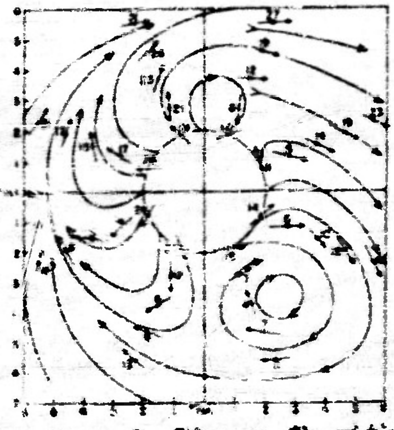


Fig. 7. Figure 6b with the average speed of storm movement, 11 knots, subtracted.

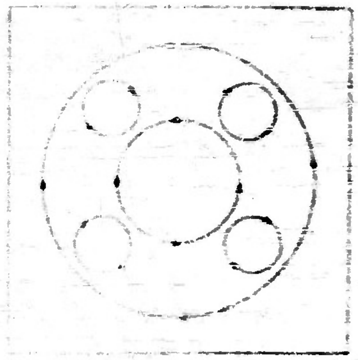


Fig. 8. Model of upper-tropospheric flow about the tropical storm.